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Advanced Control Technique for a Smart Bidirectional Electric Vehicle Charger Using Information from the National Electricity Market of Australia

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***Abstract*—Large scale adoption of electric vehicles (EVs) opens opportunities to exploit the batteries for energy storage and the regulation of electrical grids. A control technique applied to a smart bidirectional electric vehicle charger (SBEVC) could be harnessed to assist with power supply and demand of the National Electricity Market (NEM), which would improve system stability and decrease energy losses. This paper presents the control technique and tests its performance using MATLAB software based simulations of the NEM using real-world data supplied by the Australian Electricity Market Operator (AEMO). The control technique utilizes official forecast data to predict the optimal time to charge from the grid and when to discharge to the grid. The control technique uses spot price for reference. Over a month, an EV owner could "earn" 38.20 AUD if purchasing and selling at spot price (excluding levelized cost of storage). With 84 EVs implementing the control technique, at peak hour an extra 0.5 MW could be provided to the distribution system every day. This can be increased by using more powerful EV chargers. Parameters such as limiting the minimum state of charge (SoC) of the battery are used as guidelines to decrease battery degradation and to lower disruptions to the system.**

Keywords—Electric vehicles, National Electricity Market, control technique, bidirectional charger, electrical engineering, smart functionality, distribution system

I. INTRODUCTION

An electric vehicle (EV) is a vehicle that operates partially or entirely on an electric motor. Australia's adoption of EVs is continually increasing, with EV sales projected to hit 9,000,000 by 2051 [1]. Large scale adoption opens the opportunity to utilize the batteries in the vehicles for energy storage and power regulation. Vehicle-to-grid (V2G) refers to technology that allows electricity to be transferred from an EV to an electrical grid [2]-[4]. An example of this technology is a smart bidirectional electric vehicle charger (SBEVC). An SBEVC can be broken down into many integrated components; "smart" implies automation or interacting with devices and networks, and bidirectional in this case allows electricity to flow from the electrical grid to the EV (G2V) or vice versa (V2G). This allows the possibility of an EV charging and discharging at the optimal periods to reduce stress on the electrical grid, absorb renewable generation when demand is low, and supply power when demand is high. Similar products in the market function very similarly to the control technique such as Reposit [5], but the control technique discussed will focus on lowering energy losses, utilising more renewable energy and improving the efficiency of the Australian electrical distribution system. New South Wales (NSW) manages its electricity through the National Electricity Market (NEM)-a wholesale market that facilitates the trading of electricity between retailers and generators throughout Australia [6].

Through the NEM, retailers sell electricity to customers at fixed rates with added fees. The NEM is managed by the Australian Electricity Market Operator (AEMO), who maintain an array of gas and electricity markets. The AEMO website hosts a data dashboard displaying up-to-date statistics such as scheduled demand across Australia, the scheduled generation, and the current spot price [7]. Fig. 1 shows the price and demand tab in the NEM data dashboard [8].

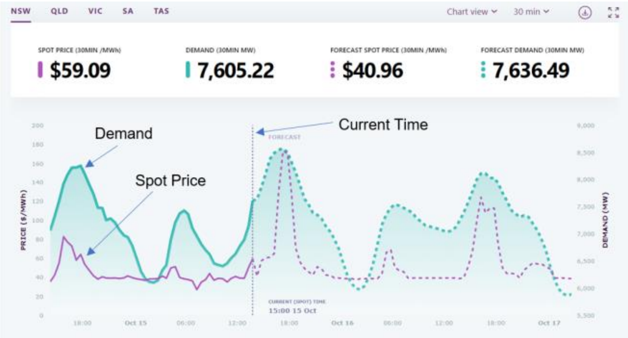

Fig. 1. Price and demand tab in the NEM data dashboard [4], [8].

Scheduled demand is demand met by scheduled generation and generation imported to the region, but excludes demand met by non-scheduled generation such as solar and wind power. It also includes the demand of local scheduled loads in that region. Scheduled generation refers to the amount of power generated by registered generators in the NEM that operate for specific periods. The spot price defines the market price electricity is sold at to retailers in the NEM. The data dashboard uses information from the Electricity Market Management System (EMMS/MMS) which also provides forecasts to the public. The data dashboard creates a forecast every 30 minutes for each region, estimating 48 hours into the future. Using this information, the research question this paper aimed to answer was: can an EV use V2G and G2V to assist with supply and demand using a control technique based on official NEM forecasts?

II. State of the Art of the Technology

A. *Electric Vehicles (EVs)*

1. EV adoption in australia

Mass adoption of EVs in NSW would impact electricity distribution both positively and negatively. This was studied by S. Rafique, G. E. Town [7] using statistical analysis of available information. Analysis showed that the average rise in electricity demand was 8% compared to actual energy consumption in 35 local government areas of NSW. If most commuter vehicles charged overnight, the excess energy stored in the EV's batteries could be pushed to the electrical grid or other vehicles if necessary. The data in this paper is outdated, even at the time of publication. It does not detail how the excess energy could be utilized via V2V or V2G. In a paper published later by the same authors [8] looking at Australia as a whole, the paper concludes that many Australians could replace their vehicles with EVs. Since 80% of vehicle trips are less than 40 km, "range anxiety" is reduced from the improved performance of newer EV models. The rise in electricity demand could be supplemented using V2V or V2G. The control technique for SBEVCs is a method that provides energy during peak demand or stores energy at peak generation. As more EVs are adopted by Australians, more power is at the ready to be distributed or stockpiled.

2. Battery

The impacts of constant charging/discharging of an EV battery can affect its overall performance. This was studied by K. Ginigeme, Z. Wang [9] who created two optimal V2G approaches to minimise peak demand, battery degradation and other factors. Calculations and case studies are used to develop the models. The paper weighs the factors of its multiple objectives to provide a baseline for a utility. Simulations of the V2G approaches were able to reduce peak demand and variance of the load profile by 7.8 and 81.9%, respectively. This improves the power system stability and energy efficiency. Like many of the other papers, real world testing was not performed, and does not outline advantages for the consumer. For the control technique, alternating between charging and discharging excessively will be prevented to give the battery a longer lifespan. Other papers suggest keeping the EVs in warmer climates to ensure maximum efficiency of the EV's battery [10]-[12].

3. Vehicle-to-grid (V2G)

The control technique discussed in this paper is aimed at making the Australian electricity distribution network more energy efficient by supplying energy when demand is high (i.e. peak hour) and absorbing excess energy when demand is low (i.e. peak generation of solar). A. Ghosh, V. Aggarwal [13] explored a menu-based pricing approach for V2G service. The user selects a contract that has different parameters for charging amounts, battery utilization and the finish time of charging. These parameters are calculated using statistical analysis, with the pricing approaches focused on profit instead of assisting with supply and demand. This paper may emphasize supporting the NEM with supply and demand on a smaller scale. By improving the power quality of a bidirectional EV charger, there will be smaller losses through charging/discharging. This will increase the usefulness of the control technique for an SBEVC. F. Barrero-Gonzalez, et al. [14] investigated EV charging station power converters with active functions. The authors created the charging station facility energy management system (CS-EMS) that sets power limits for chargers on the network alongside harmonic compensation. They tested the system using MATLAB/Simulink software. The CS-EMS was not used with real-world fast chargers and would not be used for residential use. The control technique discussed in the paper would be primarily for residential use but could also be applied in workplaces and other locations where an EV is stationary for a long period. Decreasing EV charging costs without increasing battery degradation is vital for the proposed control technique. Authors S. Amamra, J. Marco [15] created an optimized bidirectional V2G operation through a network of charging stations. The system can respond to real-time EV usage data, optimizing the system over time. The authors intend to integrate an accurate prediction model for day ahead EV parameters estimation. The control technique discussed in the paper utilizes forecasts made by the NEM, which can be used as an accurate prediction model.

B. *Control Techniques*

1. Forecasting

As SBEVCs would be continuously charging and discharging, there would be economic effects on the electrical distribution system. In Japan, the authors N Yoshioka, et al. [16] analyzed a simulation of the system using analysis of datasets and forecasting. The study examines the cost reduction effect of using V2G as system flexibility through forecasting the next day. V2G as load frequency control reduced operation cost by between 20-80 JPY per day with 180,000 EVs. Although Japan has a different distribution network and energy usage than Australia, the paper provides a positive outlook for V2G in other nations. V2G using an SBEVC would benefit the Australian distribution network, especially when Australia's energy demand is lower.

2. Power demand and supply

To create a control technique for the SBEVC, other techniques and algorithms should be considered so the control technique can perform as efficiently as possible. Two algorithms were applied in the paper written by D. Said, H. T. Mouftah [17], to find the best load management system for EVs when considering energy and cost. The paper uses extensive MATLAB/Simulink platform to test the algorithms. One algorithm schedules EVs in relation to power demand, and the other guides EVs to the best supply station for charging or discharging-both are effective in specific scenarios. The algorithms are not applied to actual EVs and the paper does not go into detail about how an EV owner would benefit from these algorithms. This paper has taken inspiration from the first algorithm but focuses on the NEM and how it can benefit the EV owner. The paper implements the control technique in the SBEVC, instead of an external load management system.

Research into different methods of integrated bidirectional control of an EV charging station led to the paper written by F. Li, et al. [18]. The paper used a space vector control strategy and instantaneous reactive power theory to build the control model which worked during simulation. The authors did not test a prototype of the EV charger to ensure it would work with any EV. The charger did not have any "smart" functionality, as the aim of the paper was to create an effective bidirectional interaction with V2G, with little detail about the charger. The "smart" functionality of the SBEVC in this paper will be the focus, as the control technique requires an internet connection for the forecast data and a processor to calculate the best course of action.

3. The National Electricity Market (NEM)

As the project is fixated on using the NEM for forecasting and information, it was best to evaluate the current state of the NEM. The paper written by H. Gu, et al. [19] reviews other journal papers and statistics to analyses the system's strength and inertia requirements. The strength of the grid is primarily determined by online synchronous generators. Distributed energy resources (DER) can degrade system security when not correctly regulated, as the distribution network is designed for unidirectional power flow, which DER disrupts. Bidirectional power flow created by an SBEVC will add to this disruption [20]. However, if the chargers are executed correctly, then the advantages will outweigh the loss of security. The control technique presented in this report will drastically affect the NEM if executed on a large-scale.

C. *Summary of the Technology*

The control technique has been formed in reference to the literature. As the probability of mass EV adoption in Australia is high [8], the control technique could be implemented on a large scale. The technique will limit the amount of times it will switch between states (e.g. discharging for a minimum period) to slow battery degradation [10] while assisting with peak demand [9]. From the various V2G methods explored, the key features taken include allowing users to enter their own parameters such as scheduling charging before driving and battery utilization [13]. The technique will also use an algorithm based on the NEM's power demand [17]. It will affect the NEM, but there are benefits for both the EV owner and Australia's distribution system [19]. Overall, a lot of the journal papers have not been tested using real world data but show potential.

III. Proposed System

1. *Control Technique*

The core objective of the proposed control technique is to assist with energy supply and demand. Discharging provides power when generation cannot keep up with demand, such as during peak hour. This would prevent extra generators turning on, potentially wasting power. Charging may conserve power that would have been lost when generation exceeds demand, such as around midday when solar generation is at its peak. This would reduce waste energy that dissipates in the distribution system. The control technique would be implemented inside a SBEVC. This can be achieved with an EV charger and a microprocessor for downloading and analyzing the forecast data. The control technique uses specific guidelines and conditions to preserve the EV battery's lifespan, as well as for the EV owner's convenience. There is the possibility of allowing the user to calibrate these guidelines, however, there needs to be baselines so the battery is not overworked. These parameters include:

- Minimum and maximum state of charge (SoC) of the EV battery (25–75%);
- Minimum period *p* where EV charges/discharges (30 minutes); and
- Scheduling recharge before the EV is used (1 hour beforehand).

Fig. 2. illustrates the logic flow of the advanced control technique, with Fig. 3. expanding the highlighted block. The NEM data dashboard provides forecast data for scheduled generation, scheduled demand and spot price. The forecast provides predictions for the next 2 days in 30-minute increments, but the control technique will redownload the forecast file every 2.5 hours. The further into the future the forecast, the less accurate the estimate is. After analysis of the different values given from the forecast, the forecast spot price is the best way for the control technique to predict trends of high and low demand. The spot price can be seen as how much the NEM is willing to pay for electricity at a point in time. When the NEM increases spot price, the distribution system requires more power to meet demand.

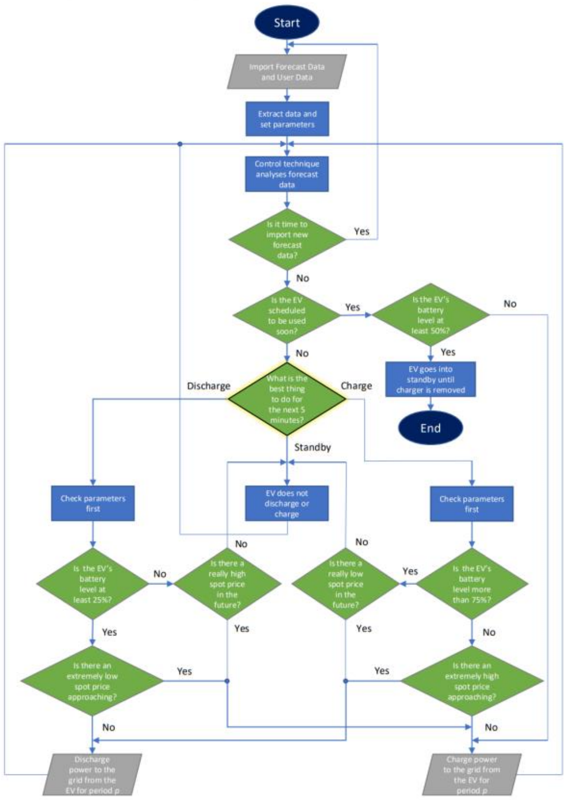

Fig. 2. Logic flowchart of the proposed advanced control technique.

As spot price rises when demand increases and vice versa, the control technique uses the spot price as its reference. When spot price is high and other conditions are met (e.g. high enough SoC, EV is not scheduled to be driven), the SBEVC will begin to discharge. When spot price is low and other conditions are met, the SBEVC begins to charge. If there isn't a particularly high or low spot price approaching, the SBEVC will standby and wait.

2. *MATLAB/Simulation Model*

To test the proposed control technique, a MATLAB simulation model of the NEM is created. The model uses both forecast data and actual data between the 6th of August 2020 to the 5th of September 2020. The simulation runs in 5-minute increments where the control technique decides its next action. There were two arrays compiled that contain 8928 values each – one containing forecasted spot prices and one with the actual spot prices of NSW. 32 forecasted data points were available to the control technique at a time as time progressed in the simulation. The battery in the simulation is modelled after the battery of a Nissan LEAF 2020. The Nissan Leaf uses a laminated lithium ion battery which is stated to have 40 kWh of capacity [21].

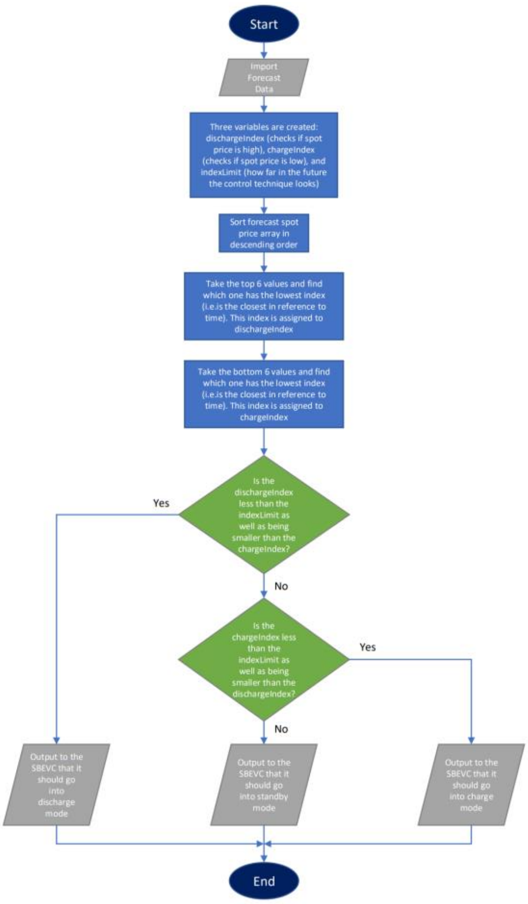

Fig. 3. Logic flowchart demonstrating how the NEM forecast data influences the advanced control technique (highlighted block in Fig. 2.)

As the battery would change capacity due to its ambient temperature, the following equation was created by F. Guo et al using Nissan LEAF data [11]:

$$Q = Q_{ref}.T_K^{0.4336}\left(0.1027.\exp\left(-\frac{14.0977}{T_K-228.0464}\right)\right) \quad (1)$$

where Q is the EV's battery capacity in megawatt hours (MWh), Q_{ref} is the rated battery capacity (in this case, 0.04 MWh), and T_K is the ambient temperature in Kelvin. The temperatures used in the simulation were the average temperatures recorded in the Wollongong area [22]. To simulate the SoC, the simulation used:

$$SoC_t = \frac{(SOC_{t-1}.Q_{t-1})+P_c-P_d-P_u}{Q_t} \quad (2)$$

where SoC_t represents the current state of charge in percent, SoC_{t-1} is the previous state of charge in percent, Q_{t-1} is the previous battery capacity in MWh, P_c is the charging power in megawatts (MW), P_d is the discharge power in MW, P_u is used power in MW, and Q_t is the current battery capacity in MWh. These values can be seen in Table I.

TABLE I. PARAMETER VALUES

Parameter	Abbreviation	Value
Rated Power of SBEVC (kW)	P_{rated}	6
Charging Power (kW)	P_c	5.98
Discharging Power (kW)	P_d	5.91
Driving Power (Wh/km)	P_{drive}	144
Rated Battery Capacity of EV (kWh)	Q_{rated}	40

The power rating of the SBEVC is 6 kW, which is one of the standard EV chargers available. To account for power losses, when charging the SBEVC will only supply 99.68% of the power to the EV and while discharging the SBEVC will only send 98.52% of the power to the grid [23]. To simulate the EV being driven, the power used is split into 2 variables. Power used driving (P_{drive}) is on average 144 Wh/km as Wollongong is in a mild climate [24]. To calculate the power used from accessories while driving (e.g. heating, ventilation and air conditioning (HVAC), radio), the following formula was derived from the studies found in [10]:

$$P_{acc} = -\frac{29}{175000}T_C + \frac{123}{35000} \quad (3)$$

where P_{acc} is the power used with accessories while the EV is driving and T_C is the ambient temperature in Celsius. Using all these parameters, the simulation will be run multiple times to create different test cases. This will be done to see what lifestyle is best suited for the control technique. It also gives EV owner's an estimate on how effective the control technique would be before implementing it in their own charger.

The simulation does not consider some parameters that may affect results. Levelised cost of storage (LCOS) for the EV battery is not taken into account and can range between 5 to 20 cents per kWh. These costs are not included in the results. Varying temperatures that simulate the EV travelling to a different area than Wollongong are not used and could affect battery capacity if the EV was driven to an area that is a different ambient temperature. Battery degradation is not tracked and could affect the battery's total lifespan. However, the simulation is accurate enough to display the control technique's performance.

IV. Results and Discussion

A. *Test Case 1: Control*

The first simulation ran with no outside variables. This means that the EV stayed connected to the SBEVC the entire month. The user did not drive at all and no power was used by the EV.

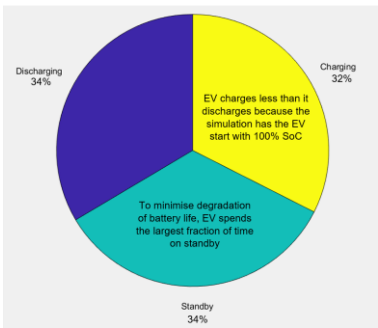

Fig. 4. Percentage of time in specific states between the 6th of August to the 5th of September 2020 for Test Case 1

Fig. 4 shows that 34% of the month was spent with the EV not charging or discharging. This can happen during periods where there are no specific peaks or drops with spot price, or when there is a long period of high spot prices where the EV's battery is drained and can no longer discharge. The control test case always shows the best performance of the control technique. This is due to the EV always being present when a high spot price is approaching. Also, power is not being used by the EV, meaning it can be discharged back to the grid and assist with high demand. Values such as how much power is discharged by the EV in total can be found in Table II. Fig. 5 shows how the battery has a larger capacity in warmer conditions. On warmer days, the battery can discharge or charge more than on colder days. This means an EV can assist more with supply and demand on these days. As the simulation only uses Wollongong's temperature, the change in battery capacity is the same across all test cases.

TABLE II. TEST CASE 1 VALUES

Simulation Variable	Value
Cumulative Power Discharged (MW)	1.475
Cumulative Power Gained (MW)	1.444
Cumulative Power Lost (MW)	0.339
Cumulative Profit[a] (AUD)	38.20

a. If power was purchased or sold at spot price and excludes LCOS

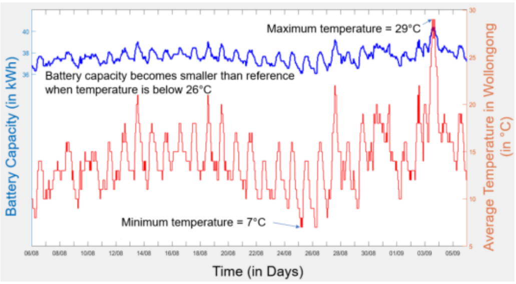

Fig. 5. Capacity of EV's battery compared to Wollongong's average hourly temperature between the 6th of August to the 5th of September 2020

B. Test Case 2: Average Week of a Worker

For this test case, the event simulated someone who drove to work while using accessories. The parameters were set as:

- Worked Monday to Friday
- Drove the average 16 km to work
- Left at 8:30am, arrived at work at 9:00am
- Left work at 5:00pm, arrived home at 5:30pm

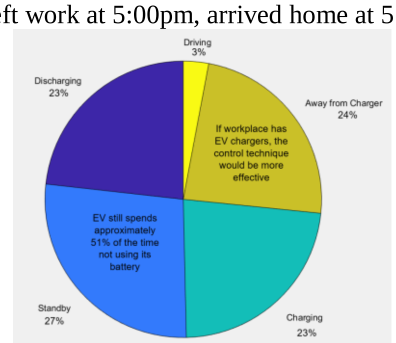

Fig. 6. Percentage of time in specific states between the 6th of August to the 5th of September 2020 for Test Case 2

Fig. 6 shows the percentage of time in specific states between the 6th of August to the 5th of September 2020 for Test Case 2. For this test case, many of the final values were much lower compared to the control case. Table III shows all the values are smaller than Test Case 1. For the total power discharged, this is due to less power being available to push back to the grid. The cumulative profit (Fig. 7) is almost halved. Peak demand usually starts around 4pm, so the control technique was not able to exploit high spot prices, as well as the fact that scheduled recharge may happen when spot price is high.

TABLE III. TEST CASE 2 VALUES

Simulation Variable	Value
Cumulative Power Discharged (MW)	1.021
Cumulative Power Gained (MW)	1.024
Cumulative Power Lost (MW)	0.236
Cumulative Power Used (MW)	0.033
Cumulative Profit[b] (AUD)	23.61

b. If power was purchased or sold at spot price and excludes LCOS

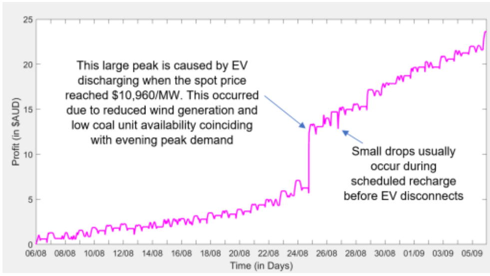

Fig. 7. Cumulative profit between the 6th of August to the 5th of September 2020 for Test Case 2

C. Test Case 3: Early Worker who Drives on Weekends

For the final test case, the simulation imitated someone who worked earlier but also drove to a destination on weekends. This case also simulated using accessories while driving. The parameters set were:

- Work:
  - Monday-Friday
  - Drove the average 16 km to work
  - Left home at 5:30am, arrived at work at 6:00am
  - Left work at 2:00pm, arrived home at 2:30pm
- Weekend:
  - Drove 20 km to location
  - Left home at 10:30, arrived at 11:30am
  - Left destination at 4:30pm, arrived home at 5:30pm

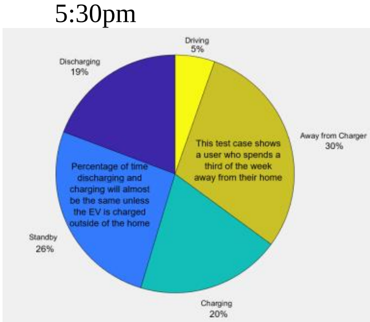

Fig. 8. Percentage of time in specific states between the 6th of August to the 5th of September 2020 for Test Case 3

Looking at Table IV, although less power has been discharged by the EV, the cumulative profit is much closer to the cumulative profit found in Test Case 2. This is due to the EV being plugged into the SBEVC closer to peak hour, assisting with peak demand when it is needed most. Although the EV is being used more and there is less energy to harness, the EV is discharging at critical times of day. Fig. 8 shows the percentage of time in specific states between the 6th of August to the 5th of September 2020 for Test Case 3.

TABLE IV. TEST CASE 3 VALUES

Simulation Variable	Value
Cumulative Power Discharged (MW)	0.847
Cumulative Power Gained (MW)	0.870
Cumulative Power Lost (MW)	0.197
Cumulative Power Used (MW)	0.055
Cumulative Profit[c] (AUD)	23.08

c. If power was purchased or sold at spot price and excludes LCOS

V. SUMMARY

Looking at the test cases, the control technique can be effective at assisting the NEM with supply and demand. The best results occur when the EV is undisturbed for long periods. For an EV owner, the control technique would be most effective with someone who works from home or gets home before peak hour demand. The control technique would not impede the owner's use of the EV, as it would charge beforehand. The EV's battery would slowly degrade due to excessive discharging, but the control technique would minimise the stress on the battery. On a small scale, the SBEVC would only discharge approximately 5.91 kW of power, which would be negligible to the NEM. However, if 87 EV's were using the control technique, that would provide an extra 0.5 MW to the distribution system. If 22 kW EV chargers were used, only 24 EVs would be required. This would improve system stability and prevent more generators coming online. Overall, the control technique would be beneficial for most EV owners, especially those who do not use their EV often or are home before peak hour.

VI. CONCLUSION

The advanced control technique can use the NEM's forecast data to accurately predict when the best time to discharge or charge would be. Using the control technique on a large scale and using EV owners with specific lifestyles would assist with NSW's power supply and demand. The results received from the MATLAB software based simulations show that there is potential for this control technique. The simulation could be improved by tracking how the battery's health would be affected, as well as LCOS. Real world testing is necessary to confirm the validity of the results presented. With continued development, the advanced control technique can be used to improve the distribution of electricity in Australia.

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